SPREAD SPECTRUM SYSTEMS

SECOND EDITION

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Robert C. Dixon

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PREFACE TO THE FIRST EDITION

Spread spectrum systems encompass communications, data transmission, message privacy, signal hiding, and position location within their repertoire. These systems are a unique blend of analog (usually RF) and digital disciplines. The coding methods used are the key to providing a spread spectrum system's capabilities.

This book represents an effort to unify at least the terminology used by those working in the spread spectrum field. It is intended to introduce working engineers and students to the philosophy and some of the details of spread spectrum technology. As far as is practical, this book is self-contained. Those who wish to dig deeper, pursue historical development, or investigate rigorous proofs will find in Appendix 3 a comprehensive listing of references in spread spectrum and related areas.

Most of the concepts of spread spectrum systems have been understood for many years, but the components and techniques for building systems capable of reliable operation have been available for a much shorter time. J. P. Costas concluded in 1959 that "for congested-band operation, broadband systems appear to offer a more orderly approach to the problem and a potentially higher average traffic volume than narrow-band systems." At that time, however, transistors and other components were not available to build a reliable, reasonably sized spread spectrum system.

Today components have advanced to the point at which large parts of a spread spectrum system can be contained in a single integrated circuit. A code generator, for instance, which even in 1967 would have required at least 100 discrete transistors, can easily be incorporated in a single small package only slightly larger than one of the transistors. In the future a complete subsystem may well be reduced to one similarly small package. The point is that the use of spread spectrum techniques is no longer constrained by *constituent electronic* components, within limits.

Spread spectrum applications started with the first communicator who set up a scheduled time to send and receive messages. This scheduling may have come about through a desire to avoid heavy traffic (consider, for instance, 10 Indian smoke signalers talking at once) or a desire to avoid interception by surprising the would-be interceptor. The same technique of timing was adapted by radio operators, but they added a new dimension—frequency. The radio operator not only could schedule his transmissions for a time unknown to an interceptor but could transmit at one of many frequencies, which forced the interceptor to "find" his transmission in addition to guessing his schedule. Encoding of messages for error correction and improved time and frequency selection naturally followed.

Modern spread spectrum communications circuits and systems have evolved from just these simple concepts. Both of the most important communications and data systems (frequency hopping and direct sequence) use code-controlled frequency-time keying to avoid interception and minimize interference. These systems have grown in capability and in application since the late 1940s and have been applied today in many areas. Though almost all of the applications to date have been military, commercial equipment is available, and the major test equipment manufacturers have introduced instruments specific to the spread spectrum area.

The material in this book has been gathered from many sources—technical articles, internal memos, military contract reports, private conversations, and my personal experience. References are listed whenever they were available.

The first chapter is an introduction to spread spectrum systems and the reasons for their being. Chapter 2 describes the different types of systems in some detail. Subsystems are described in Chapters 3 through 8, with the emphasis placed on describing advantages and disadvantages of various implementations. Also, successful designs typical of real systems are included. Application of spread spectrum techniques is the subject of Chapter 9. I hope that some ideas for new applications will be generated by this chapter.

The gestation period for this book has spanned a number of years. The idea for it came about in 1963. Since then many people have contributed to its growth. A list of those who have influenced it would fill another book. Edward Guyer of the Northrop Corporation, P. M. Hooten and C. F. White of the Naval Research Laboratories, R. D. Matson and H. J. Schmidt of the Air Force Avionics Laboratories, D. R. Bitzer of D. O. D., and Dr. I. J. Gabelman of Rome Air Development Center all are due special thanks for their help in bringing the book to reality.

To those who insist on strict rigor and abundance of mathematical precedence no apology is given. There is enough of this material already existing to define completely all that is said here many times over. That is precisely the problem I have tried to overcome—hoping to separate enough of the trees from the forest that the usefulness and practical aspects of spread spectrum systems can be seen—simply and in their own context—without the myriad qualifying statements and assumptions that would otherwise be required. There are, listed within the bibliography of this book, enough of the works of those whose world is rigor and precedence to satisfy the needs of their fellows.

Those who, like me, are afflicted with the need for practical applications to secure their understanding have, I hope, found a book useful to them.

ROBERT C. DIXON

Cypress, California
June 1975

Preface

The idea of organizing a conference on cavitation was born at the 8th International Symposium on Nonlinear Acoustics in Paris, 1978. This idea took further shape during a visit of Dr. L. Bjørnø to Göttingen where the final decision concerning the scope of the conference was made. We both felt the need to pierce the walls of traditional areas and to bring together specialists from related fields for fruitful interaction. Cavitation bubbles in liquids may be looked at as a kind of disturbance in an otherwise homogeneous medium and subsumed under the heading of *inhomogeneities*. A quick discussion revealed that so much work was in progress all over the world as to make an exchange of ideas really worthwhile. Thus the first conference on *Cavitation and Inhomogeneities in Underwater Acoustics* was set forth and entered a state of strong and serious activity beginning in July 1978 and culminating in the Proceedings now at hand.

As expected the conference brought together a wide variety of topics and characters and a vivid exchange of ideas. At least five sections were found necessary to group the papers: *Cavitation, Sound Waves and Bubbles, Bubble Spectrometry, Particle Detection* and *Inhomogeneities in Ocean Acoustics*.

In *Cavitation* (Part I) the new method of producing cavitation by photons has led to renewed attack on problems which some time ago were thought to be beyond the reach of experimenters, e.g., the bubble collapse problem. This well-established problem curiously reappears in a very modern context in connection with the laser driven collapse of hollow targets in laser fusion studies. But this topic was considered too far removed from the scope of this conference and therefore not included.

When bubbles are present in a liquid they may strongly influence the passage of sound waves (Part II). Indeed, such effects as shock wave and soliton formation, self-induced transparency and, of course, frequency mixing effects are reported. This terminology strongly bears relationship to the newly expanding field of nonlinear optics.

Inhomogeneities in the form of bubbles strongly determine the nonlinear properties of the medium. Therefore quite an effort has been undertaken from different sides to measure their size distributions (Part III). Acoustical and optical methods and extensive computer processing are involved in accomplishing this task.

Project DUMAND (Deep Undersea Muon and Neutrino Detection) was included as a special topic to show of how underwater acoustics may become relevant to farther removed fields in physics. The acoustical detection of astrophysical neutrinos in the ocean (Part IV) is a challenge to every ocean acoustician. But in order not to expand the conference in too many directions bubble chamber problems were not included.

Inhomogeneities also appear in the ocean on a larger scale than ordinary bubbles. They may not be so easily seen as bubbles, but due to the long distances involved they have a marked influence on sound propagation. The mixing of water of different temperatures and salinities gives rise to local sound speed variations. Currents, tides, eddies, and internal waves do likewise. These topics are covered in Part V.

A Congress cannot be organized without the aid of many helping hands and minds. First of all I want to thank Dr. L. Bjørnø for his steady help in all questions concerning the organization. He shared much of my burden and kept a watchful eye on bottlenecks in the countdown towards the conference. Then there was the help of the International Advisors Committee

V.A. Akulichev, USSR
R.E. Apfel, USA
P.A. Crowther, UK
V.A. Krasil'nikov, USSR
H. Medwin, USA
E.A. Neppiras, UK
A. Prosperetti, Italy

in suggesting topics and lecturers. My special thanks here go to Dr. H. Medwin for his activities.

Our cheerful Local Organizing Committee from the Third Physical Institute where the conference took place:

K.J. Ebeling
E. Cramer
G. Haussmann
W. Hentschel
R. Timm
A. Vogel
B. Binnewies
H. Präkelt

made things function smoothly without interruption during the days of the conference. They, with their whole-hearted input were the sponsors of the conference making other sponsors superfluous.

Last but no least I admire the patience of Mrs. B. Binnewies and Mrs. H. Präkelt in executing the editorial work that partly turned out to become real labour. In the editorial work I obtained the help of Dr. J. Burt which is greatly appreciated. Many figures were redrawn by Mrs. Liebe for the benefit of the reader. The photographic work was done by Mrs. Kirschmann-Schröder. All this necessary work caused some delay in publishing but I hope will be compensated for by the final appearance of the book.

Herewith it is rendered to the scientific community.

Göttingen, December 1979 *Werner Lauterborn*

CONTENTS

1 THE WHATS AND WHYS OF SPREAD SPECTRUM SYSTEMS 1

1.1 What is a Spread Spectrum System? 1
1.2 Why Bother? 7
1.3 Process Gain and Jamming Margin, 9

2 SPREAD SPECTRUM TECHNIQUES 13

2.1 Direct Sequence Systems, 15

Characteristics of Direct Sequence Signals, 16
Radio Frequency Bandwidth in Direct Sequence Signals, 21
Direct Sequence Process Gain, 25
Direct Sequence Code and Spectrum Relationships, 27
The Minimum Shift Key Technique, 28

2.2 Frequency Hopping, 28

Characteristics of Frequency Hopping Signals, 29
Determining Frequency Hopping Rate and Number of Frequencies, 34
Avoiding the Repeat Jammer, 40

2.3 Time Hopping, 42

2.4 Pulsed FM (Chirp) Systems, 44

Characteristics of Chirp Signals, 44

2.5 Hybrid Forms

Frequency Hopped/Direct Sequence Modulation, 48
Time-Frequency Hopping, 52
Time Hopping Direct Sequence, 53

3 CODING FOR COMMUNICATIONS AND RANGING 56

3.1 Maximal Sequences, 58

Run-Length Distribution, 60
Autocorrelation, 61
Linear Addition Properties, 62
State Exhaustion, 64

3.2 Linear Code Generator Configuration, 64

3.3 Autocorrelation and Cross-correlation of Codes, 71

3.4 Composite Codes, 79

Gold Code Sequence Generators, 79
Syncopated-Register Generators, 82
JPL Ranging Codes, 83

3.5 Bit Rate and Code Length, 84

3.6 Choosing a Linear Code, 86

3.7 Generating High Rate Codes, 91

3.8 Software-Implemented Codes, 97

3.9 Code Selection and Signal Spectra, 98

3.10 Code Baseband Spectra, 103

3.11 Error Detection and Correlation Codes, 104

4 MODULATION AND MODULATORS: GENERATING THE WIDEBAND SIGNAL 108

4.1 Balanced Modulation, 109

Effects of Carrier and Code Rate Spurious (Lack of Suppression), 117
Quadriphase Modulation, 117
Carrier Modulation Trade Offs, 120
Effect of Synch Acquisition, 120
Sidelobe Energy Output, 121

4.2 Frequency Synthesis for Spread Spectrum Modulation, 126

Indirect Synthesis, 131
Direct Synthesis, 132
Synthesis from Digital Words, 136

4.3 Sending the Information, 136

Carrier Modulation, 138
Clock Rate Modulation, 139
Code Modification, 141
Digitizing Methods, 142
Frequency Hopping Code Modifiers, 149

5 CORRELATION AND DEMODULATION 153

5.1 Remapping the Spread Spectrum, 153

In-Line Correlation, 154
Heterodyne Correlation, 156
Code Timing Offset Effects on Correlation, 158

5.2 Effect of Nonsynchronous Input Signals, 162

Correlator Output with Interference, 167
Direct Sequence Reaction to Interference, 171
Frequency Hopping Reaction to Interference, 181

5.3 Baseband Recovery, 186

Phase-Lock Loops, 187
Squaring Loops, 191
Costas Loop Demodulators, 193
Frequency Modulation Feedback Demodulators, 196
PDM Demodulation, 198
Frequency Hopping Demodulation, 198
Integrate-and-Dump Filters, 203
The Dehopped Signal, 204
m-ary Detection, 210

6 SYNCHRONIZATION 214

SOURCES OF SYNCHRONIZATION UNCERTAINTY, 214

6.1 Initial Synchronization, 217

The "Sliding" Correlator, 218
Synchronization Preambles, 221

Frequency Hop Synchronization, 223
Transmitted-Reference Methods, 224
Universal Timing, 226
Burst Synchronization, 226
Sequential Estimation, 227
Special Coding for Synch Acquisition, 228
Matched-Filter Synchronizers, 229
Synch Recognition, 234

6.2 Tracking, 248

Tau-Dither Tracking, 248
Delay-Lock Tracking, 252
Split-Bit Tracking, 257
Coherent Loss Due to Bandpass Filtering, 258

7 THE RF LINK, 261

7.1 Noise Figure and Cochannel Users, 261

7.2 Dynamic Range and AGC, 265

7.3 The Propagation Medium, 272

Line-of-Sight Loss, 272
Absorptive Losses, 273
Differential Phase Delay, 274
Multipath, 275

7.4 Overall Transmitter and Receiver Design, 278

The Transmitter, 279
Power Amplification, 280
VSWR, 283
Receiver RF Considerations, 283
Receiver Signal Handling Capacity, 284
Wideband Front Ends, 284
The Ideal RF Section, 285
Bandwidth and Phase-Shift Effects, 288

8 NAVIGATING WITH SPREAD SPECTRUM SYSTEMS 291

8.1 Ranging Techniques, 291

Tone Ranging, 295
Sources of Range Error, 296

Frequency Hopping Range Measurement, 298
More on the Selection of a Clock Rate, 298
Selecting the Ranging Code, 300
Hybrid-Ranging System, 301

8.2 Direction Finding, 306

Special Antennas, 306

9 APPLICATIONS OF SPREAD SPECTRUM METHODS 313

Space Systems, 313
Avionics Systems, 325
Test Systems and Equipment, 330
Message Protection, 334
Position Location, 334
Real Systems, 335
A Final Word, 335

APPENDIX 1 GLOSSARY OF TERMS 336

APPENDIX 2 BIBLIOGRAPHY ON SPREAD SPECTRUM SYSTEMS AND RELATED TECHNOLOGY 342

APPENDIX 3 EQUIVALENCE OF SIMPLE AND MODULAR SEQUENCES 388

APPENDIX 4 MULTIPLICATION OF DIRECT SEQUENCE SIGNALS 390

APPENDIX 5 LINEAR CODE SEQUENCE VULNERABILITY 392

APPENDIX 6 THE RELATION BETWEEN ω_n AND $\omega_{3\,\mathrm{dB}}$ 398

APPENDIX 7 GOLD CODE SELECTION 403

ANSWERS TO PROBLEMS 406

INDEX 419

1

THE WHAT AND WHYS OF SPREAD SPECTRUM SYSTEMS

Spread spectrum techniques, applied in recent years, have produced results in communications, navigation, and test systems that are not possible with standard signal formats. In many applications the advent of high-speed transistors and / or integrated circuits was the key to practical-sized-and-powered equipment based on spread spectrum modulation. But what is a spread spectrum system? What are the advantages of spread spectrum modulation? To be sure, there are also disadvantages, but what are they?

These questions and others are posed in this chapter and in those that follow. It is hoped that the reader will find the answers he or she needs in a useful form.

1.1 WHAT IS A SPREAD SPECTRUM SYSTEM?

Before we attempt to define a spread spectrum system, let us be sure that we understand what is meant by a spectrum. Every transmitting or modulating system has a characteristic signature that includes not only the frequency at which the signal is centered, but also the bandwidth of the signal when modulated by the intended signaling waveform. A spectrum, as we speak of it here, is the frequency-domain[1703] representation of the signal and, for our purposes, especially the modulated signal. We most often see signals presented in the time domain (that is, as functions of time). Any signal, however, can also be presented in the frequency domain, and transforms (mathematical operators) are available for converting frequency- or time-domain functions from one domain to the other and back again. The most basic of these operators is the Fourier transform, for which the relationship between the time and frequency domains is defined by the pair of integrals

$$F(f) = \int_{-\infty}^{\infty} f(t) \exp(-j\omega t)dt$$

which transforms a known function of time to a function of frequency, and

$$f(t) = \int_{-\infty}^{\infty} F(f) \exp(j\omega t)df$$

which performs the inverse operation.

Fourier transforms do not exist for some functions because they require the existence of the integral

$$\int_{-\infty}^{\infty} f(t)\, dt$$

Therefore discontinuous signals must often be transformed by use of the Laplace integral

$$L(s) = \int_{0}^{\infty} f(t) \exp(-st)\, dt$$

Tables of Fourier and Laplace transform pairs for many functions have been generated and well documented (e.g., see 1714 and 1716).

Figure 1-1 illustrates some of the Fourier transforms that are most important in our considerations of spread spectrum systems. For example, we will be interested in the spectra of carriers modulated by pseudorandom binary data streams. Also of some interest will be the spectra of frequency hopped carriers—especially where those carriers are to be used in multiple-access applications, and it is necessary to restrict any interference between mutual users of the same band of frequencies. Note that the frequency spectrum produced by modulation with a square pulse is a (sin x)/x function, while modulation having a (sin x)/x envelope produces a square spectrum. Other spectra that will be of special interest to us are those that are produced by triangular or trapezoidal envelopes and the Gaussian-shaped pulse. Still others will be introduced in the following chapters.

Even as an oscilloscope is a window in the time domain for observing signal waveforms, so is a spectrum analyzer a window in the frequency domain. The many spectrum presentations in this book are almost all spectrum analyzer representations, generated by sweeping a filter across

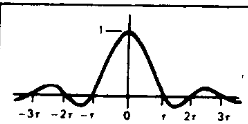
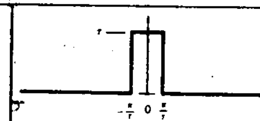
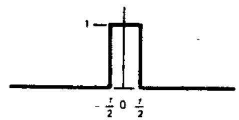
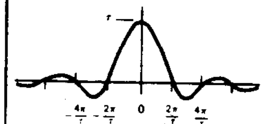
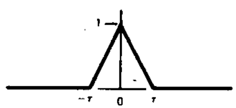
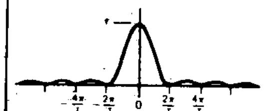
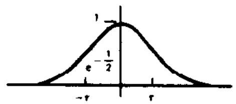
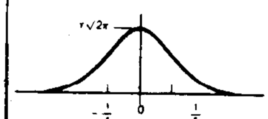
	Time function		Frequency function		
$\frac{\sin x}{x}$ Envelope		$f(t) = \frac{\sin(\pi t/\tau)}{\pi t/\tau}$	$F(\omega) = \begin{cases} \tau, \lvert\omega\rvert < \pi/\tau \\ o, \lvert\omega\rvert > \pi/\tau \end{cases}$		Rectangular frequency spectrum
Rectangular envelope		$f(t) = \begin{cases} 1, \lvert t\rvert < \tau/2 \\ o, \lvert t\rvert > \tau/2 \end{cases}$	$F(\omega) = \tau \frac{\sin(\omega\tau/2)}{\omega\tau/2}$		$\frac{\sin x}{x}$ Frequency spectrum
Triangular envelope		$f(t) = \begin{cases} 1 - \lvert t\rvert/\tau, \lvert t\rvert < \tau \\ o, \lvert t\rvert > \tau \end{cases}$	$F(\omega) = \tau \frac{\sin^2(\omega\tau/2)}{\omega\tau/2^2}$		$\left(\frac{\sin x}{x}\right)^2$ Frequency spectrum
Gaussian envelope		$f(t) = e^{-(t/\tau)^2/2}$	$F(\omega) = \tau\sqrt{2\pi}\, e^{-(\tau\omega)^2\, 2}$		Gaussian frequency spectrum

Figure 1.1 Four important Fourier transforms and their corresponding time and frequency functions.

the band of interest and detecting the power falling within the filter as it is swept. This power level is then plotted on an oscilloscope. All spectra referred to are power spectra.

Literally, a spread spectrum system is one in which the transmitted signal is spread over a wide frequency band, much wider, in fact, than the minimum bandwidth required to transmit the information being sent. A voice signal, for example, can be sent with amplitude modulation in a bandwidth only twice that of the information itself. Other forms of modulation, such as low deviation FM or single sideband AM, also permit information to be transmitted in a bandwidth comparable to the bandwidth of the information itself. A spread spectrum system, on the other hand, often takes a baseband signal (say a voice channel) with a bandwidth of only a few kilohertz, and distributes it over a band that may be many megahertz wide. This is accomplished by modulating with the information to be sent and with a wideband encoding signal.

The most familiar example of spectrum spreading is seen in conventional frequency modulation in which deviation ratios greater than one are used. Bandwidth required by an FM signal is a function not only of the information bandwidth but of the amount of modulation. As in all other spectrum spreading systems, a signal-to-noise advantage is gained by the modulation and demodulation process. For FM signals this gain advantage (referred to as "process gain") is

$$3\beta^2\left(\frac{S}{N}\right)_{\text{info}}$$

where β = deviation ratio, or $\Delta f_{\text{carrier}}/f_{\text{modulation}}$,
$(S/N)_{\text{info}}$ = signal-to-noise ratio in the baseband or information bandwidth.

Wideband FM could be classified as a spread spectrum technique from the standpoint that the RF spectrum produced is much wider than the transmitted information. In the context of this book, however, only those techniques are of interest in which some signal or operation other than the information being sent is used for broadbanding (or spreading) the transmitted signal.

Three general types of techniques will be accepted here as examples of spread spectrum signaling methods:

1. Modulation of a carrier by a digital code sequence whose bit rate is much higher than the information signal bandwidth. Such systems are called "direct sequence" modulated systems.
2. Carrier frequency shifting in discrete increments in a pattern dictated by a code sequence. These are called "frequency hoppers." The